Dual-Mode Free-Jet Combustor

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Outline

- Historical Perspective
- Dual-Mode Free-Jet Combustor Concept
- Results of First CFD First Campaign
- Results of Second CFD Campaign
- Summary

Historical Perspective

RJ43-MA-3
circa 1950

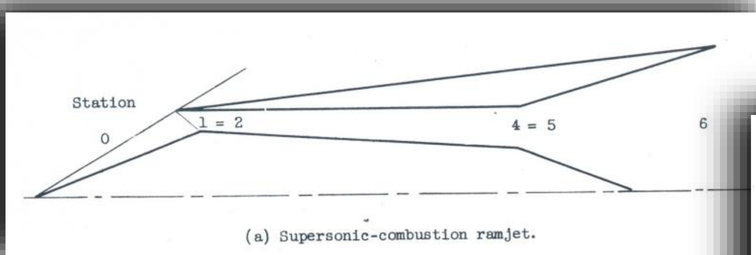
1910 2020

Ramjet Development (104)

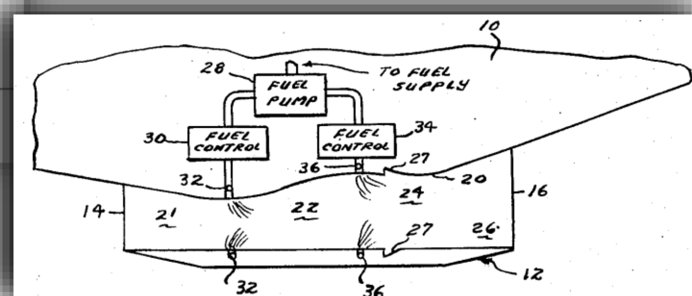
1913
Lorin

Scramjet Development (62)

“Dual-Mode” Ramjet Development (45)



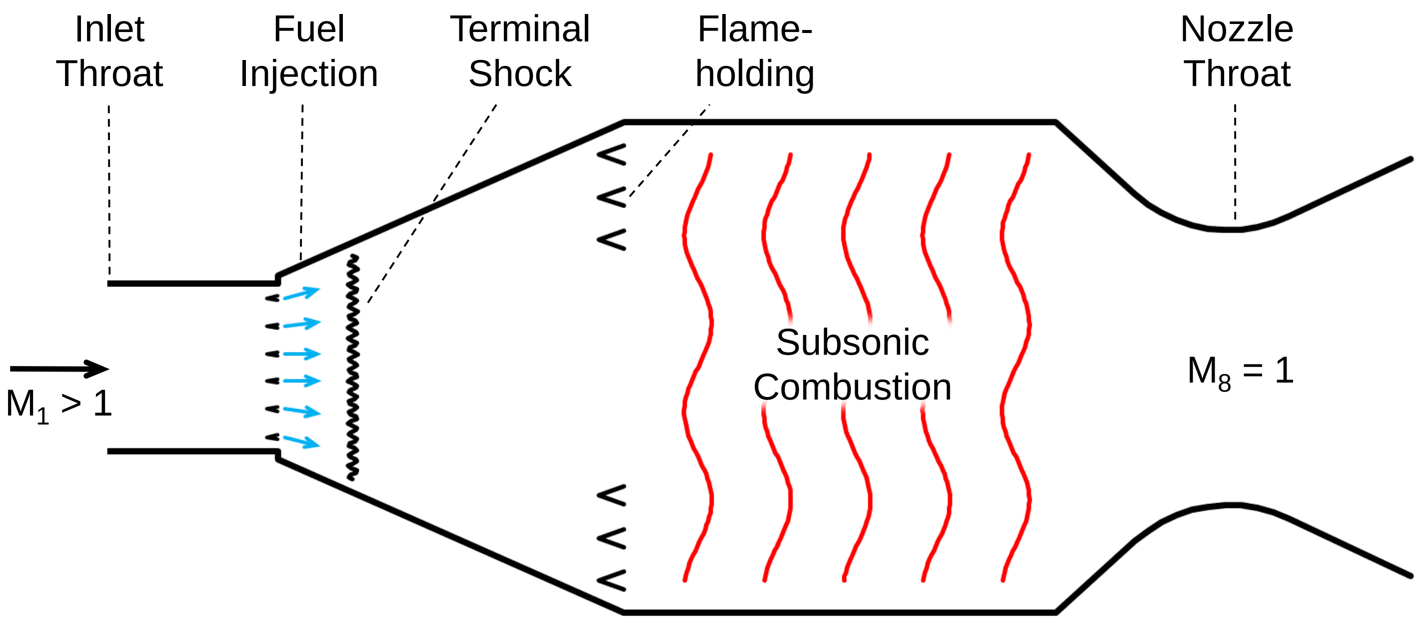
Weber and MacKay
1955



Curran and Stull
1972

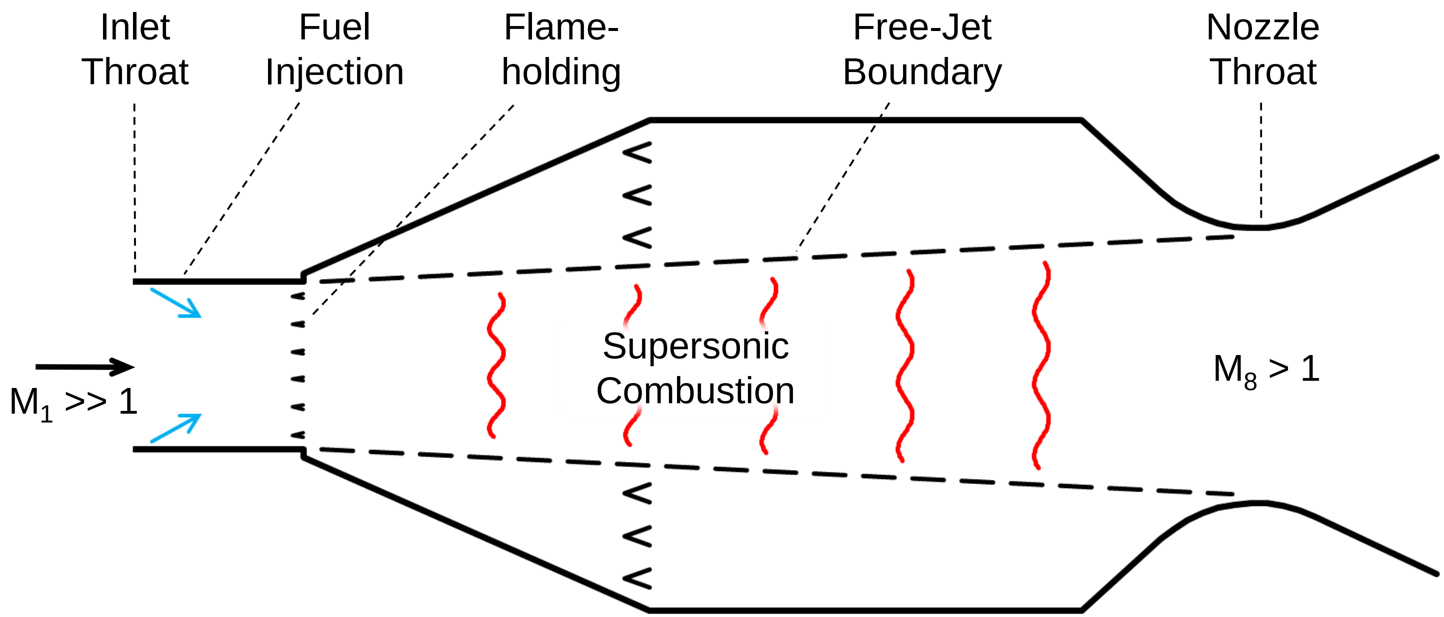
Dual-Mode Free-Jet Combustor

Subsonic Combustion Ramjet Mode



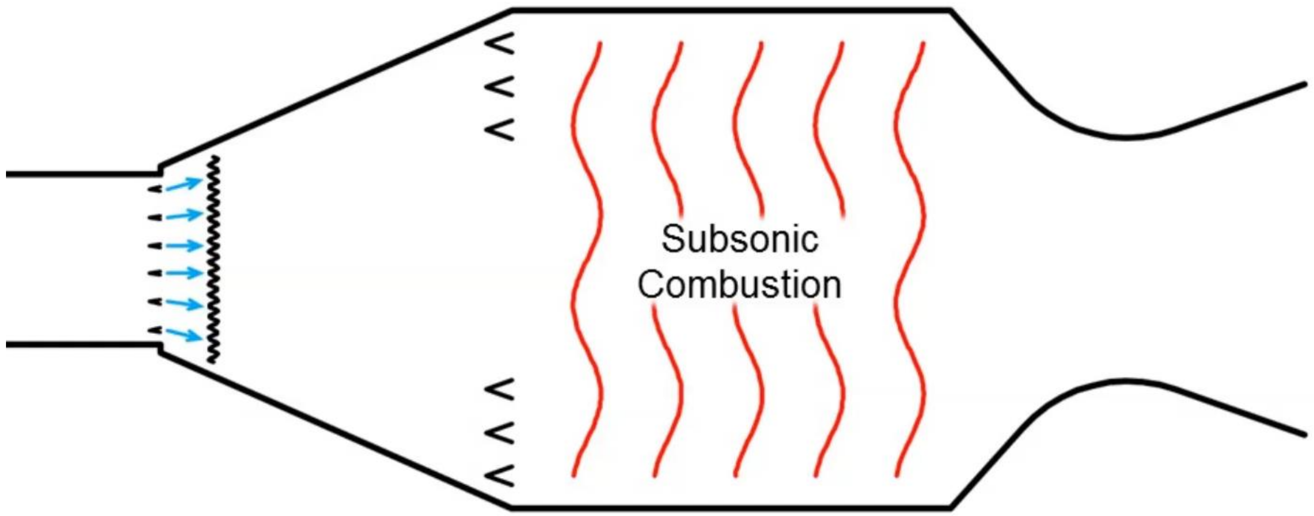
Dual-Mode Free-Jet Combustor

Supersonic Free-Jet Combustion Mode



Dual-Mode Free-Jet Combustor

Transition Animation



Supersonic free-jet mode was analyzed in two separate CFD campaigns:

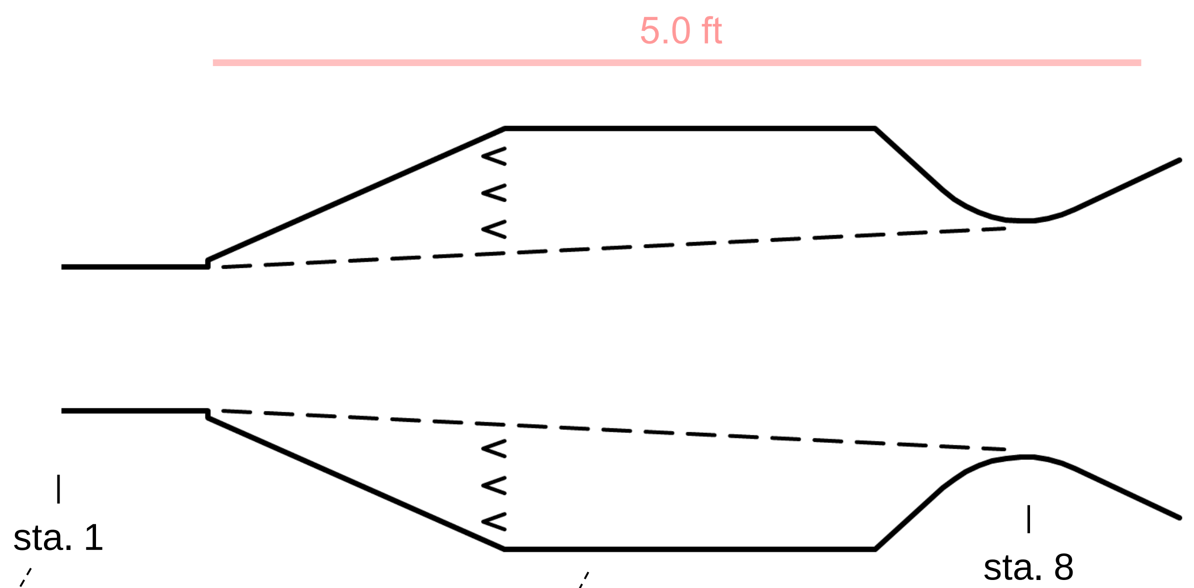
1) RANS with equilibrium chemistry for free-jet proof-of-concept
   - Mach 5, 8, and 12 flight conditions
   - Axial fuel injection through choked annular slots
   - Effect of nozzle throat area
   - Reported in 2010 AIAA paper

2) Time-accurate RANS with finite-rate chemistry to increase fidelity
   - Focus on Mach 8 flight condition
   - Fuel and air pre-mixed, flameholders added
   - Effect of nozzle throat area and other parameters
   - Reported in 2015 JANNAF paper

This paper will summarize highlights from both campaigns and present latest results not previously published

Subsonic combustion ramjet mode, nor mode transition have been analyzed to date

Flowpath Sizing and Inlet Conditions



Inlet throat area (sta. 1) is variable, based on inlet contraction ratio schedule

Combustion Chamber Diameter Sized for Subsonic Combustion at a Mach 2.5 Flight Condition

Nozzle throat area (sta. 8) is variable, based on constant-pressure supersonic combustion or ramjet inlet flow matching

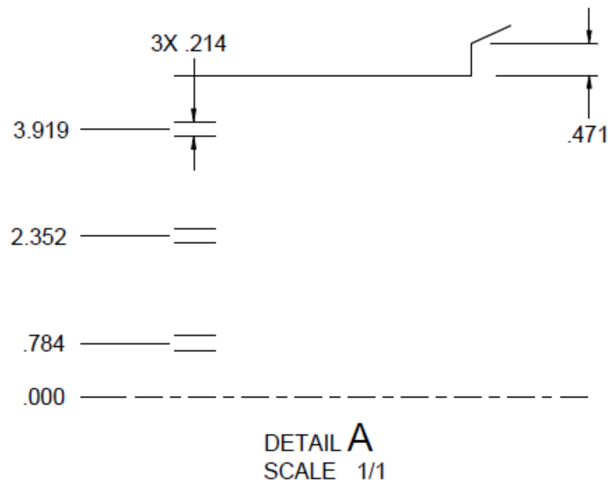
Flight Mach Number, M_0	Freestream Stagnation Temp, $T_{T,0}$ (R)	Inflow Pressure, P_1 (lb/in^2)	Inflow Temp, T_1 (R)	Inflow Velocity, V_1 (ft/sec)	Inflow Mach Number, M_1 (ref)	Nozzle Area Ratio, A_8/A_1	Air Flow Rate, $\dot{m}_a$ (lb/sec)	Ethylene-Air Equilibrium Temperature $T_{T,EQ}$ (R)
5	2,225	27.26	1321	3509	2.00	3.743	97.4	5,074
6	2,982	25.25	*1594	4544	2.42	3.323	95.4	5,428
8	4,833	21.77	1966	6531	3.08	2.709	81.1	6,360
10	7,163	22.99	*2609	8316	3.38	2.198	71.9	7,717
12	10,085	25.29	3714	10055	3.51	1.833	63.2	9,682

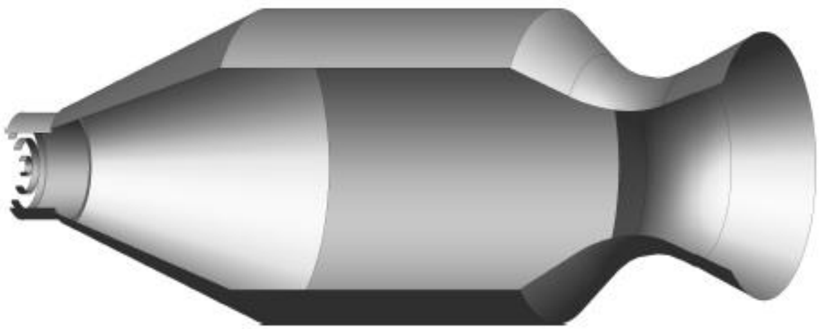
GASP CFD Code

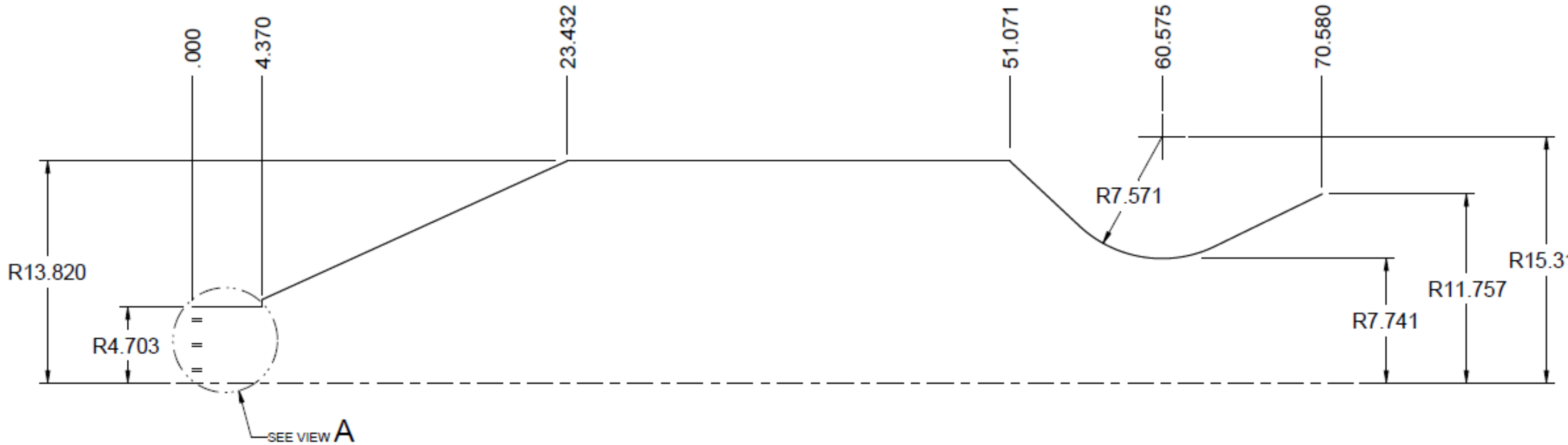
- GASP Version 5 - Commercial code by Aerosoft, Inc.
- Reynolds-Averaged Navier-Stokes equations
- Menter Shear Stress Transport (SST) turbulence model with compressibility correction
- 8-Species, 3-reaction Baurle ethylene-air chemistry model in equilibrium mode (infinite reaction rates)
- 3rd-order, upwind-biased Roe scheme
- 414,000 grid points
- Initial calculations with adiabatic walls
- Constant-temperature walls for evaluation of heat load

Geometry for GASP CFD Calculations

Mach 8 Case Shown

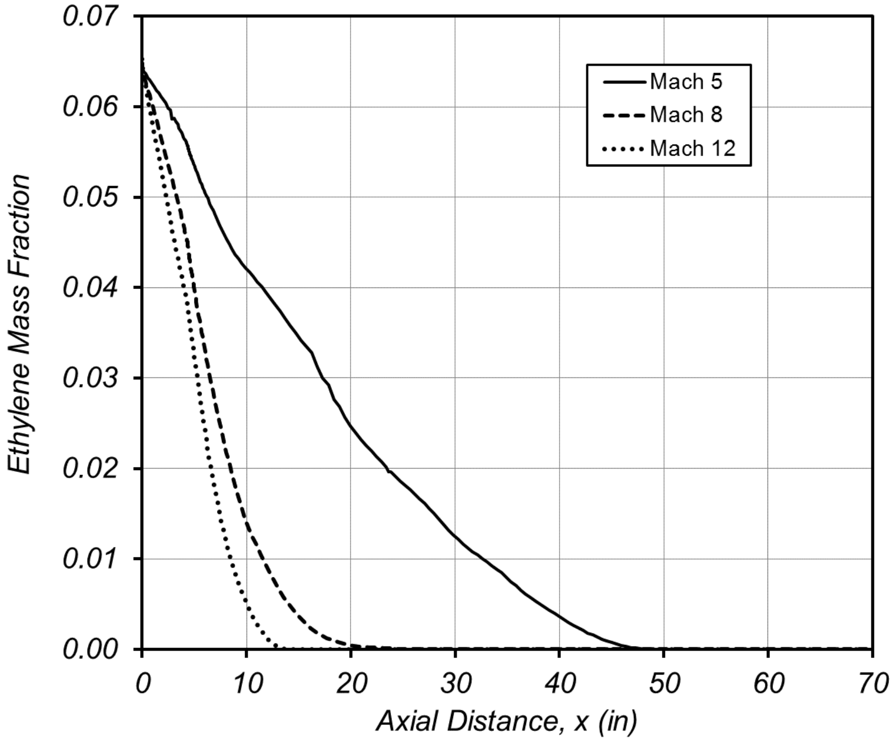


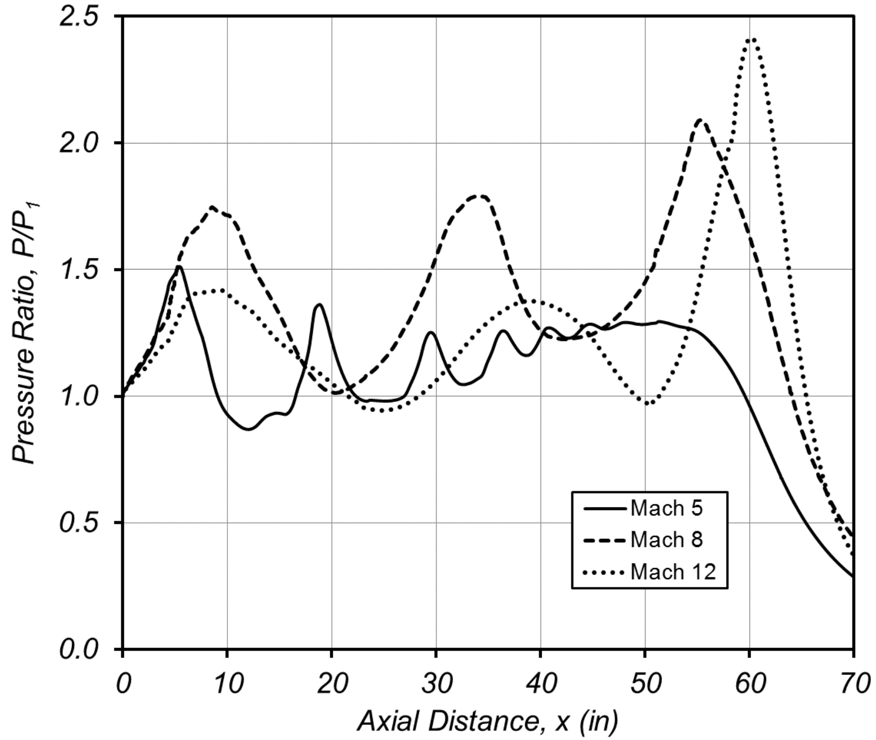




GASP Equilibrium Chemistry Results

Ethylene Mass Fraction and Pressure Distributions

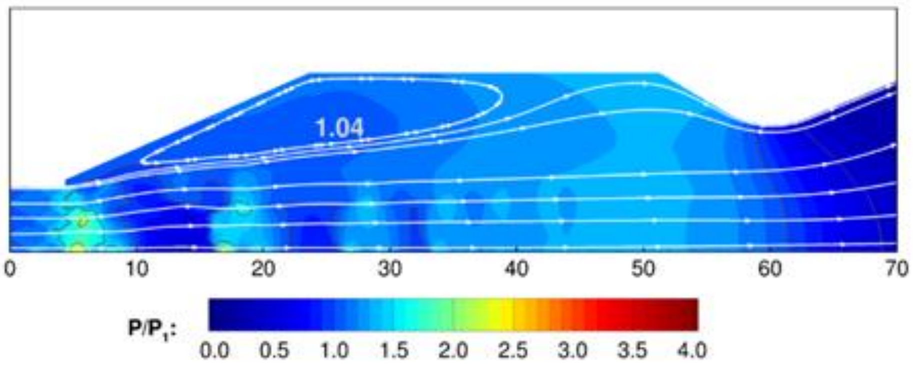




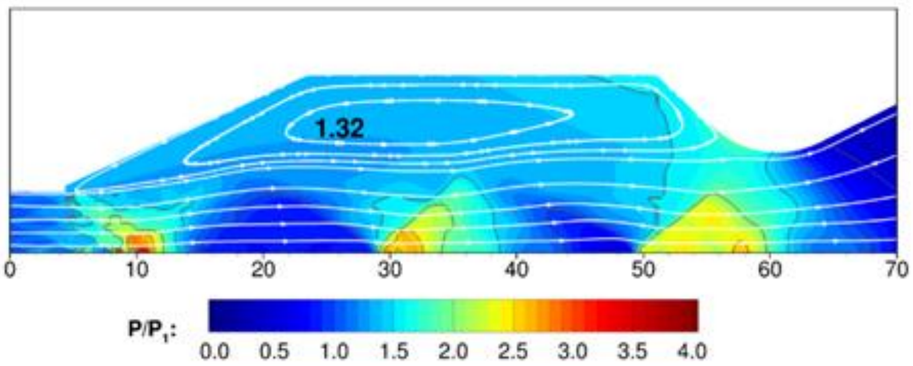
GASP Equilibrium Chemistry Results

Pressure Contours and Streamlines for Mach 5, 8, and 12

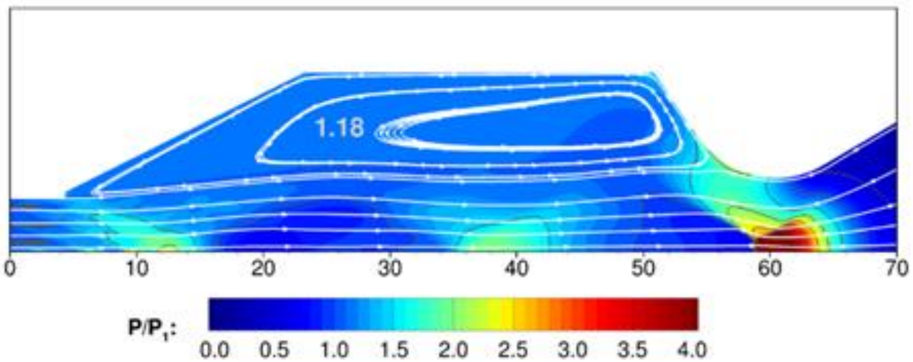
Mach 5 flight condition
(2 injectors)



Mach 8 flight condition
(3 injectors)



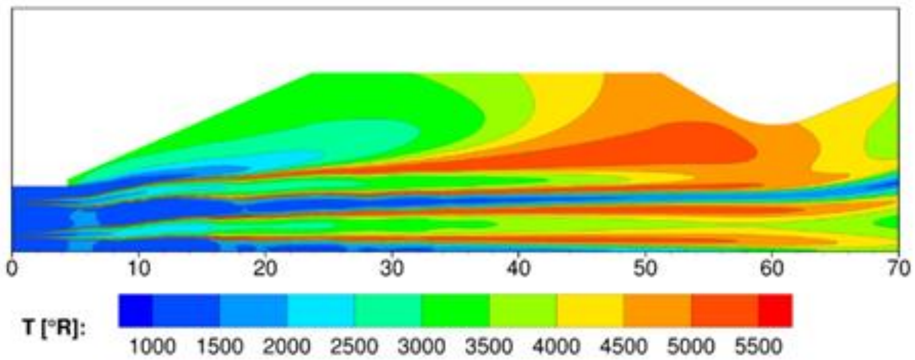
Mach 12 flight condition
(3 injectors)



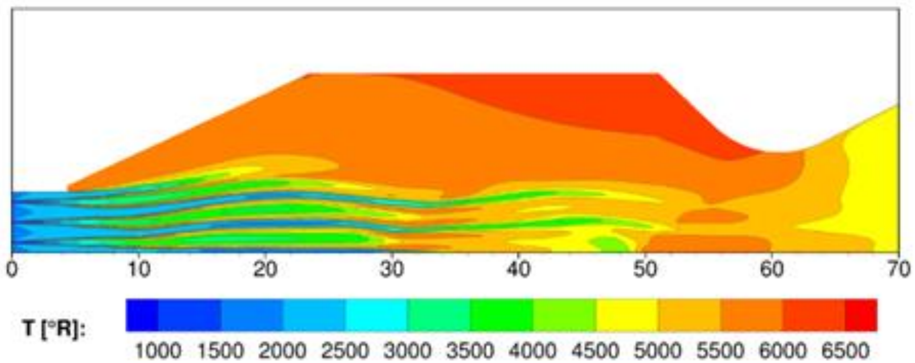
GASP Equilibrium Chemistry Results

Temperature Contours for Mach 5, 8, and 12

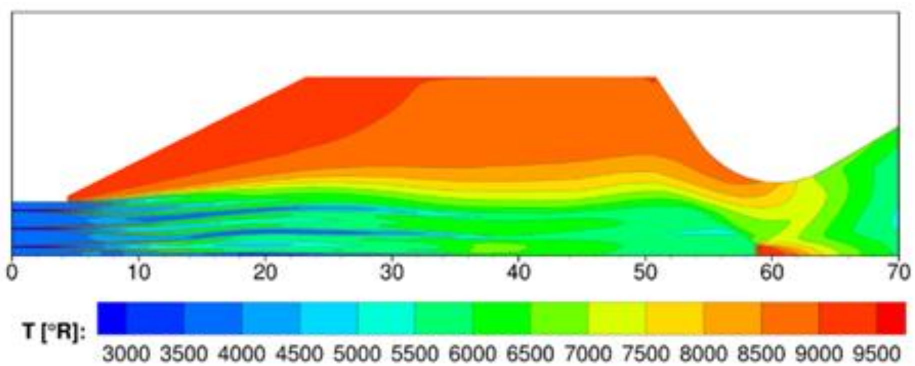
Mach 5 flight condition
(2 injectors)



Mach 8 flight condition
(3 injectors)

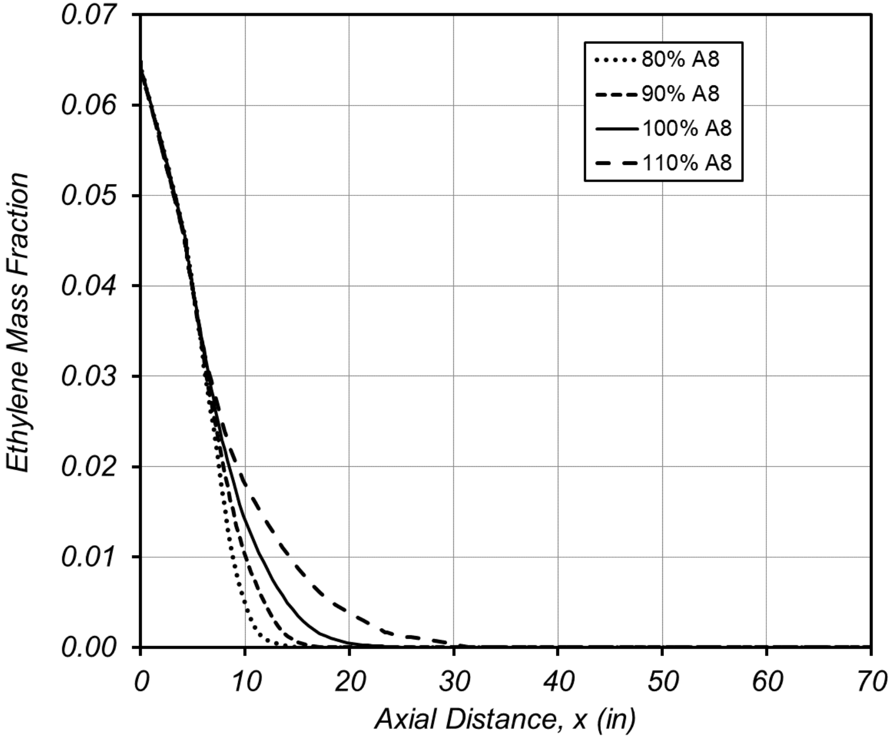


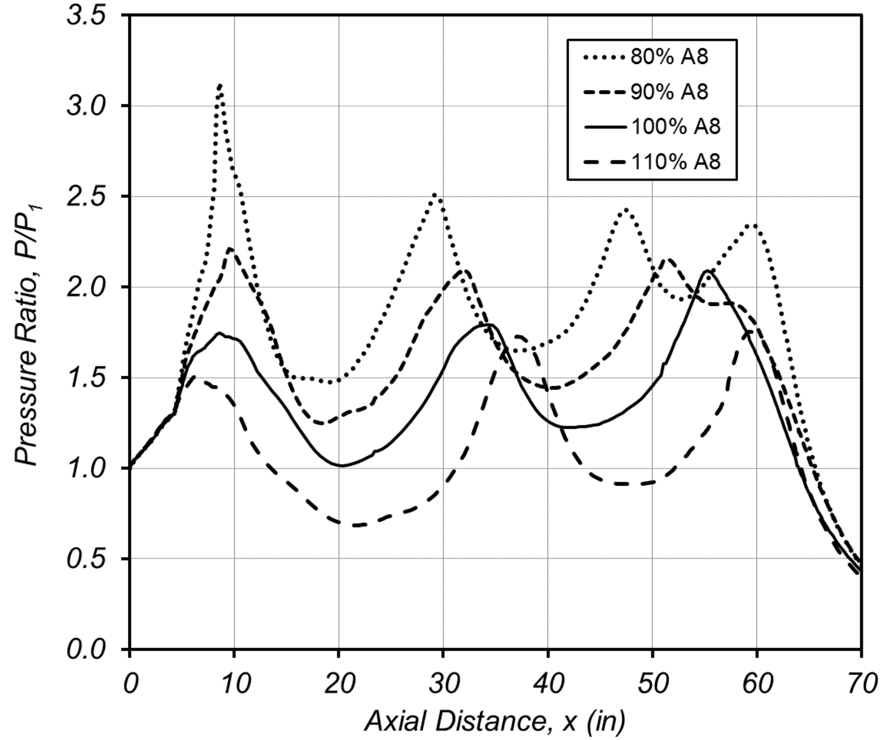
Mach 12 flight condition
(3 injectors)



GASP Equilibrium Chemistry Results

Effect of Nozzle Throat Area, Mach 8 Flight Condition





GASP Equilibrium Chemistry Results

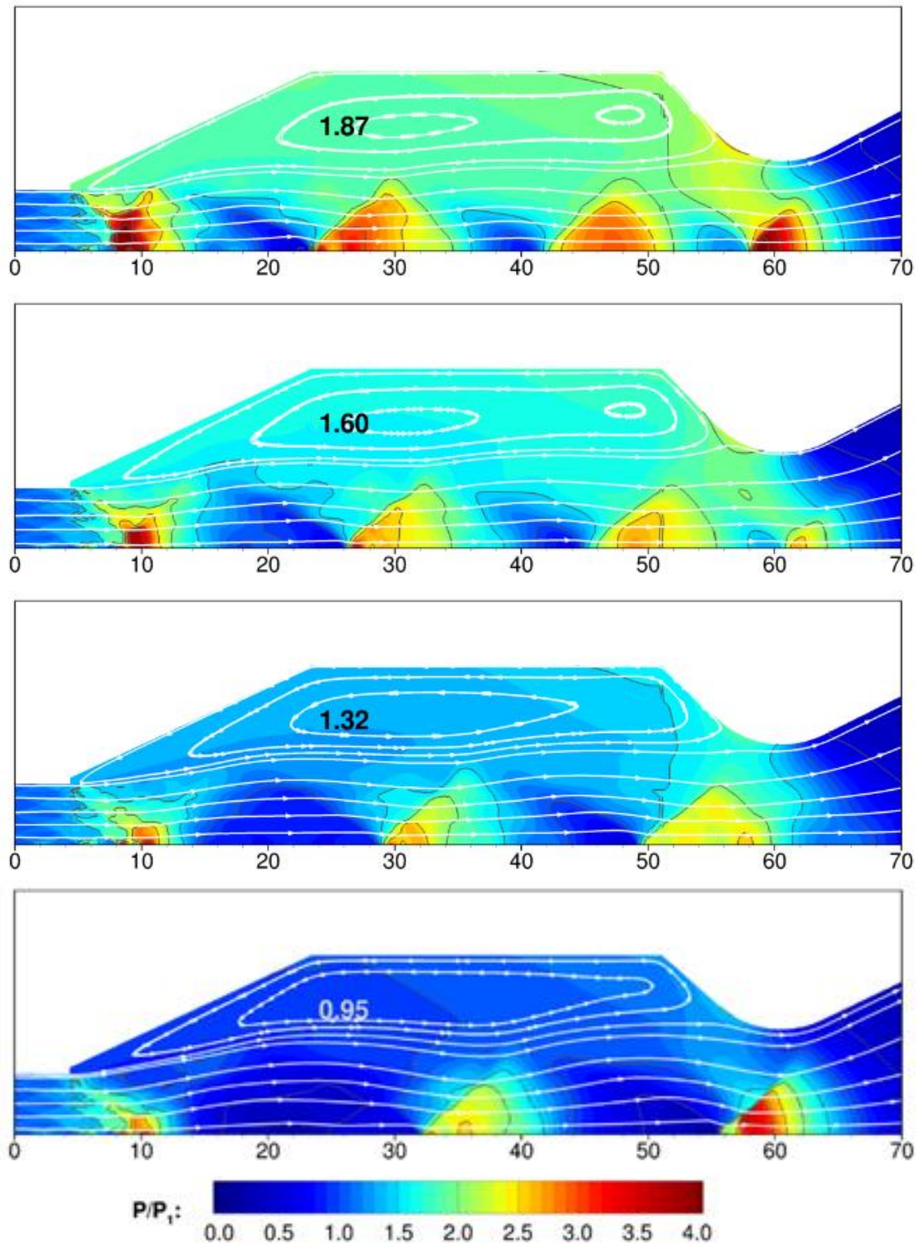
Effect of Nozzle Throat Area on Pressure Field

80% Nozzle Throat Area

90% Nozzle Throat Area

100% Nozzle Throat Area

110% Nozzle Throat Area



GASP Equilibrium Chemistry Results

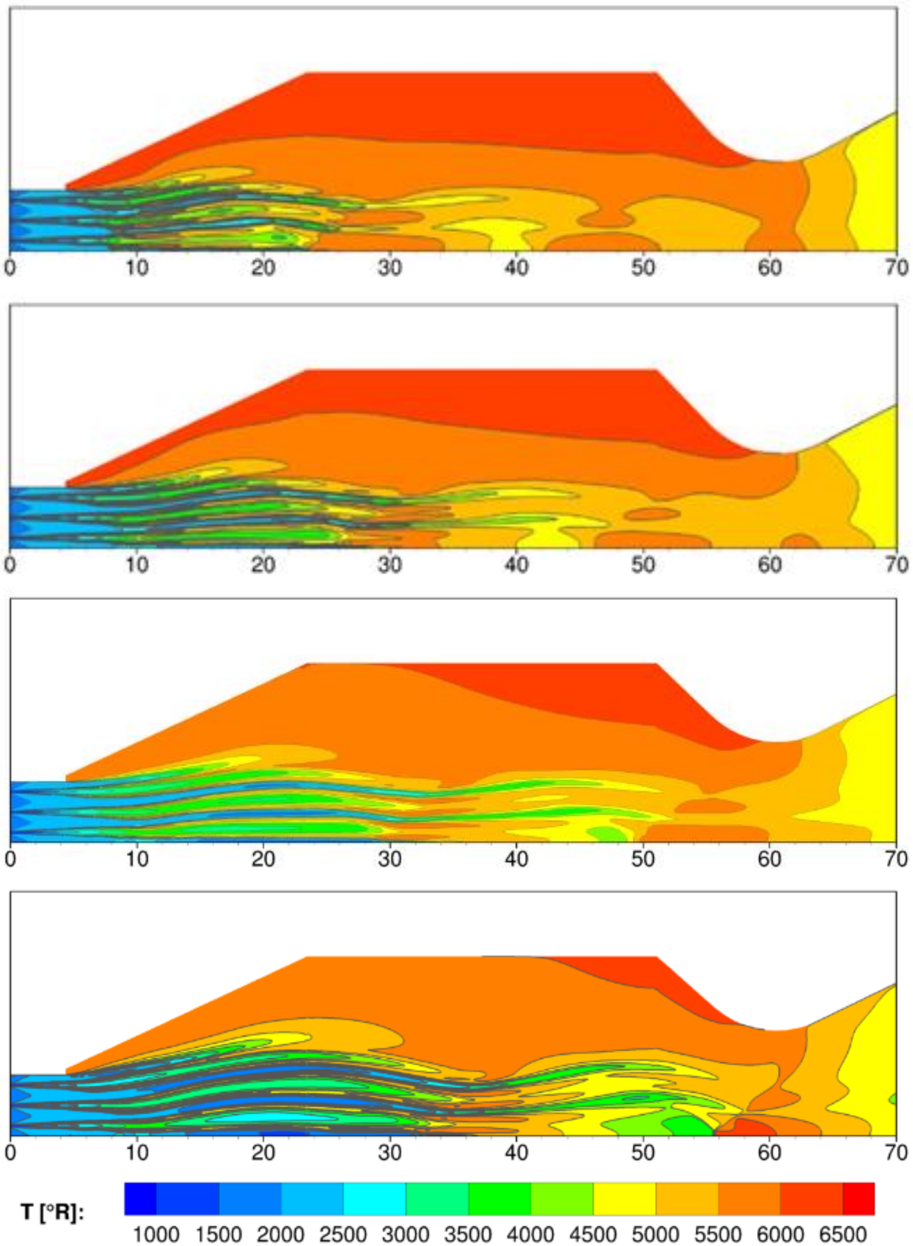
Effect of Nozzle Throat Area on Temperature Field

80% Nozzle Throat Area

90% Nozzle Throat Area

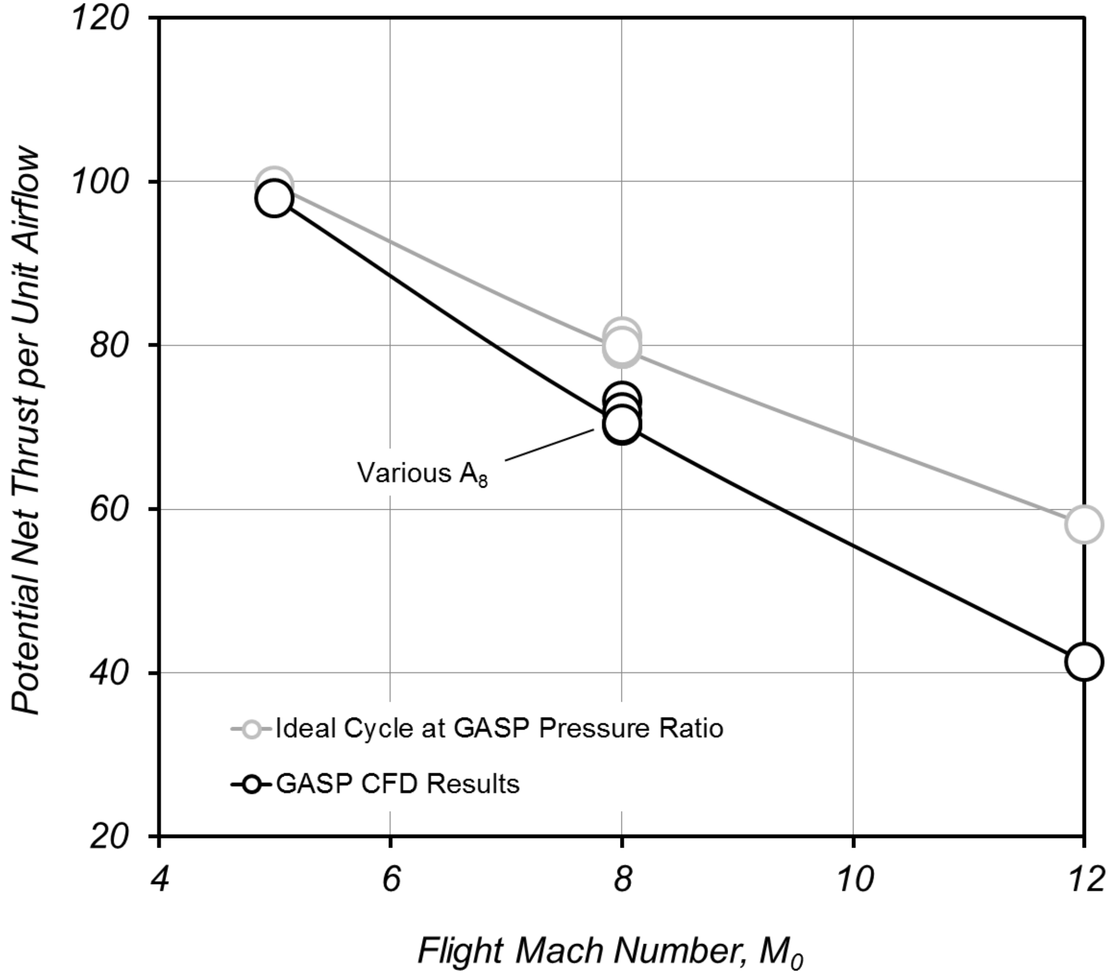
100% Nozzle Throat Area

110% Nozzle Throat Area



GASP Equilibrium Chemistry Results

Performance Compared to Standard Cycle

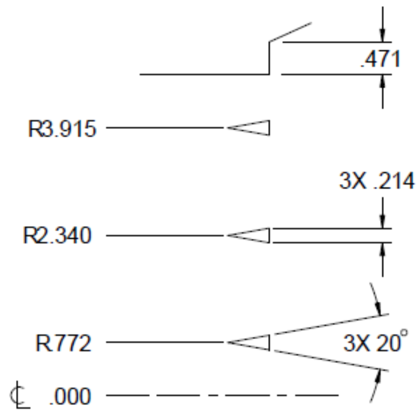


TAFI CFD Code

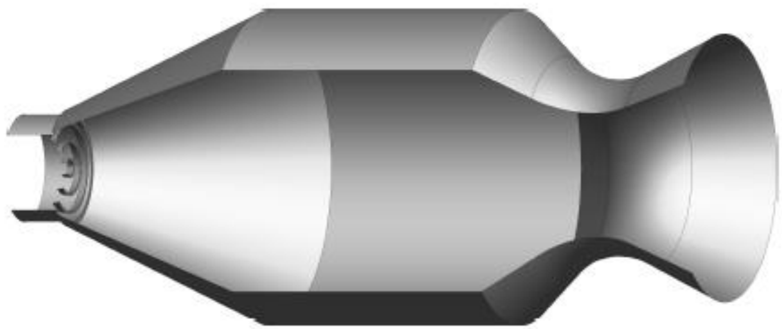
- Time-accurate, fully-implicit (TAFI) code developed in-house at NASA GRC
- Reynolds-Averaged Navier-Stokes equations
- Spalart-Allmaras one-equation turbulence model was used with a constant value of 0.9 for the turbulent Prandtl and Schmidt numbers
- 9-Species, 10-reaction Singh and Jachimowski reduced ethylene-air combustion mechanism
- Grid consisted of 24 blocks with a total of 136,840 grid points
- Initial calculations with adiabatic walls
- Constant-temperature walls for evaluation of heat load

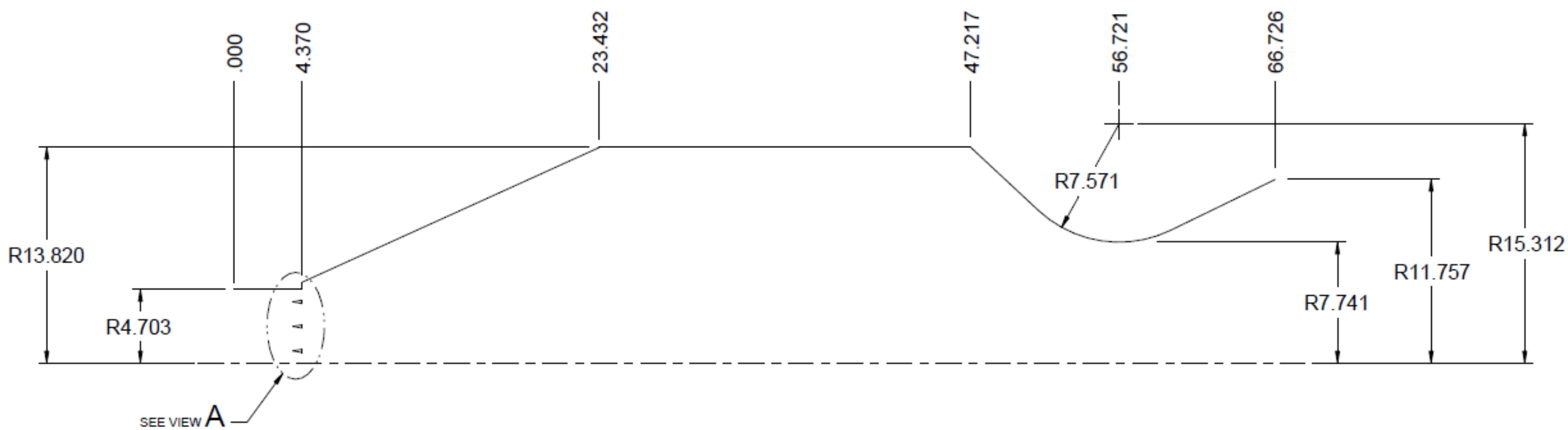
Geometry for TAFI Finite-Rate CFD Calculations

Mach 8 Case Shown

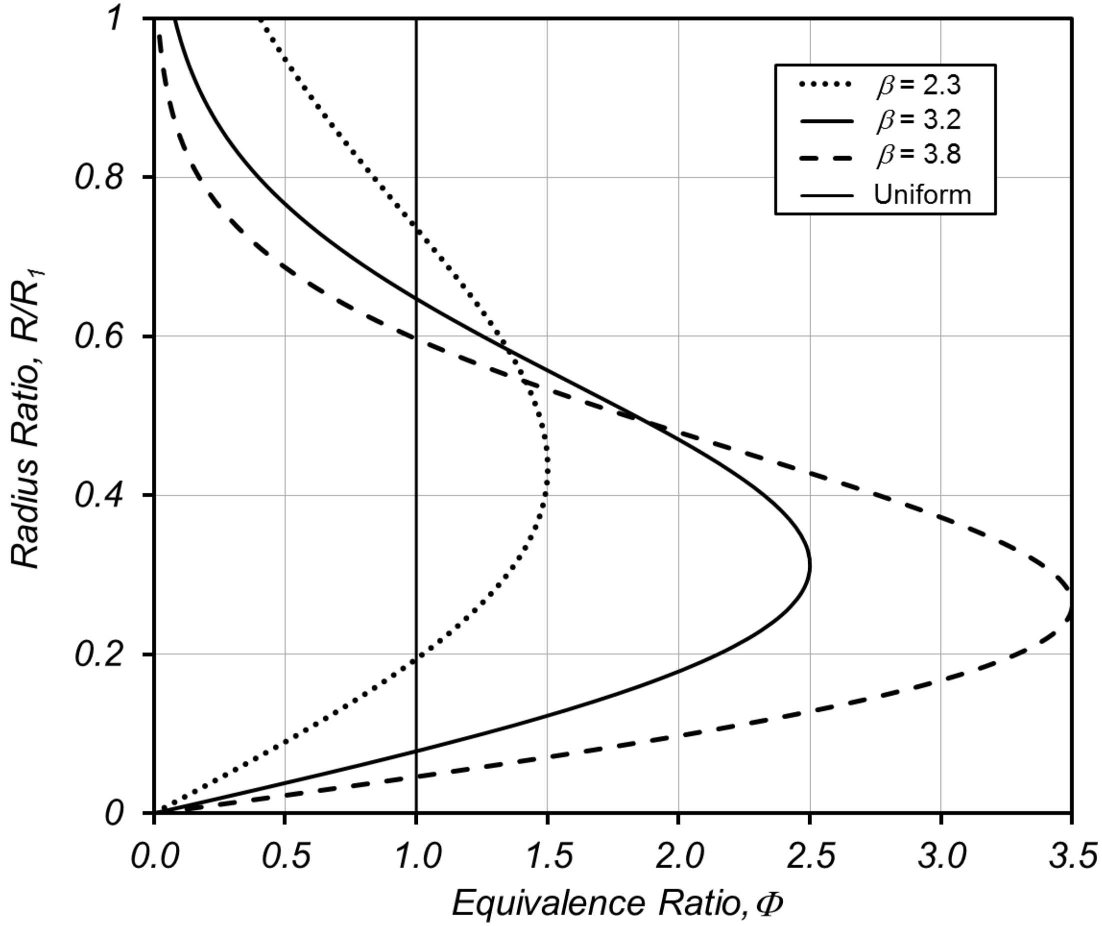


DETAIL A
SCALE 1/1



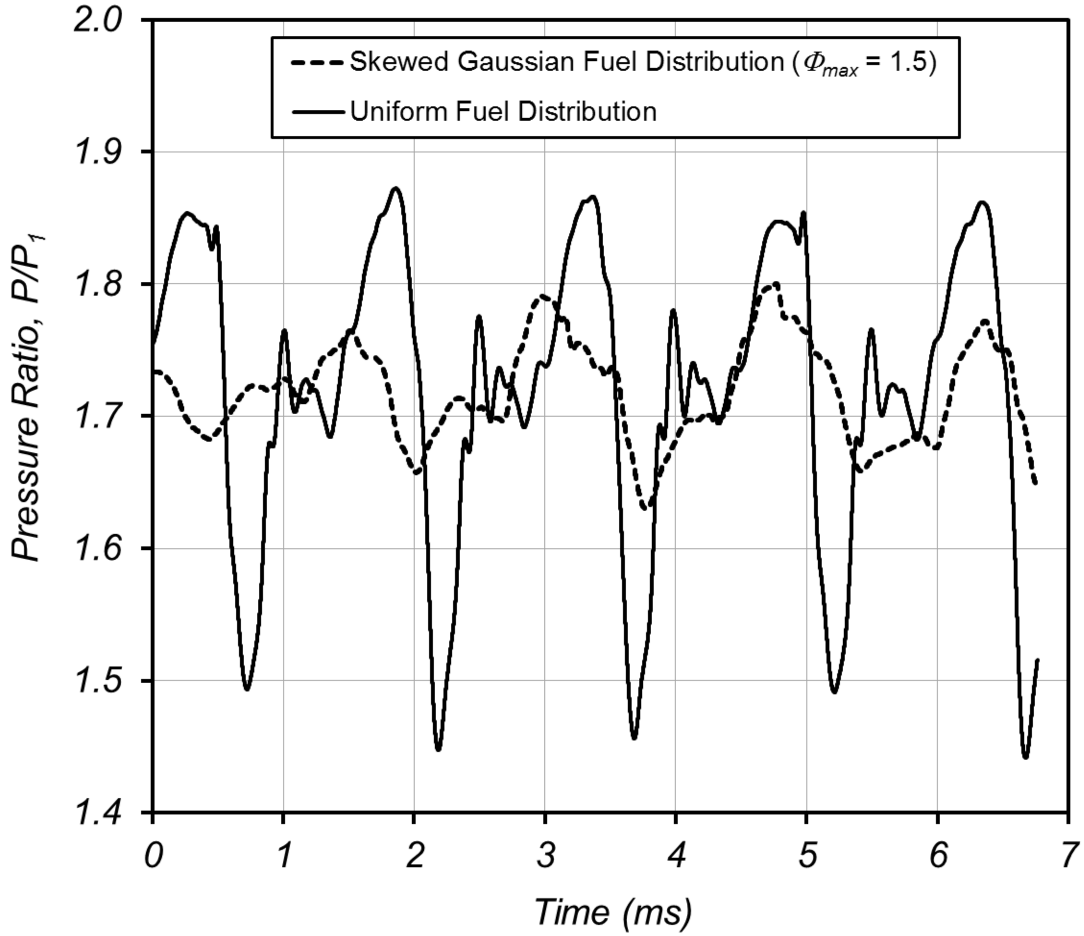


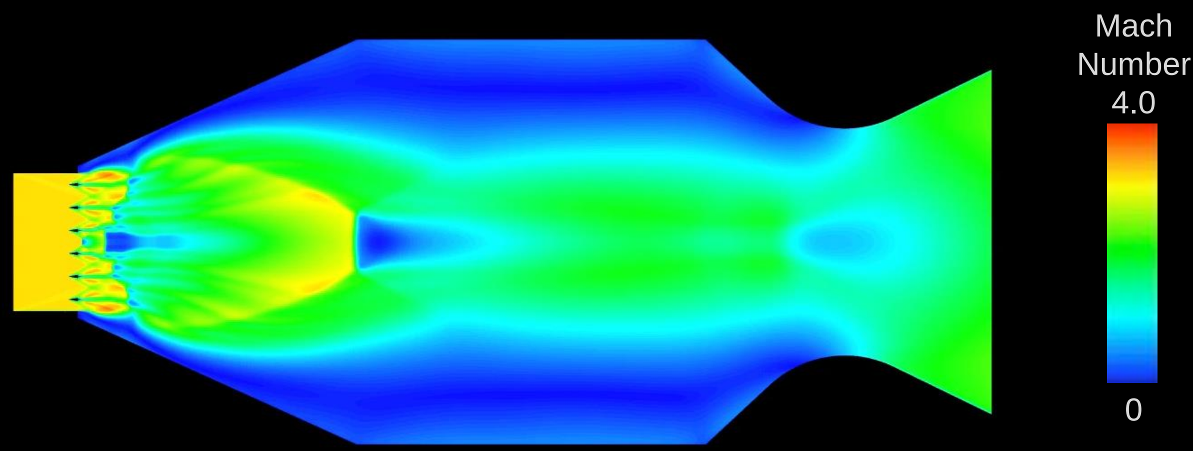
Skewed Gaussian Fuel Inflow Profiles

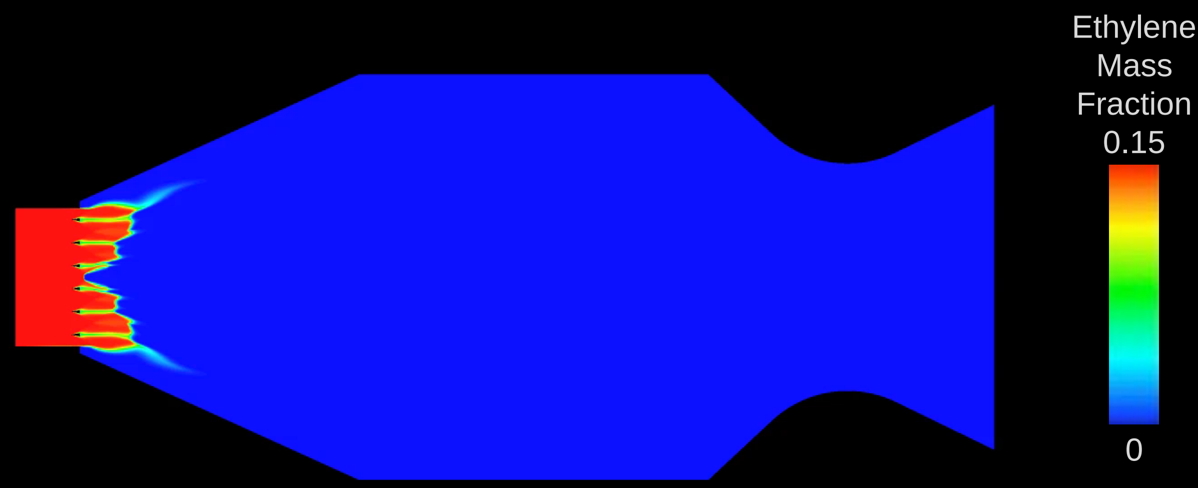


TAFI Finite-Rate Chemistry Results

Solutions Periodic for Uniform and low Φ_{max} Cases, Mach 8 Flight Condition

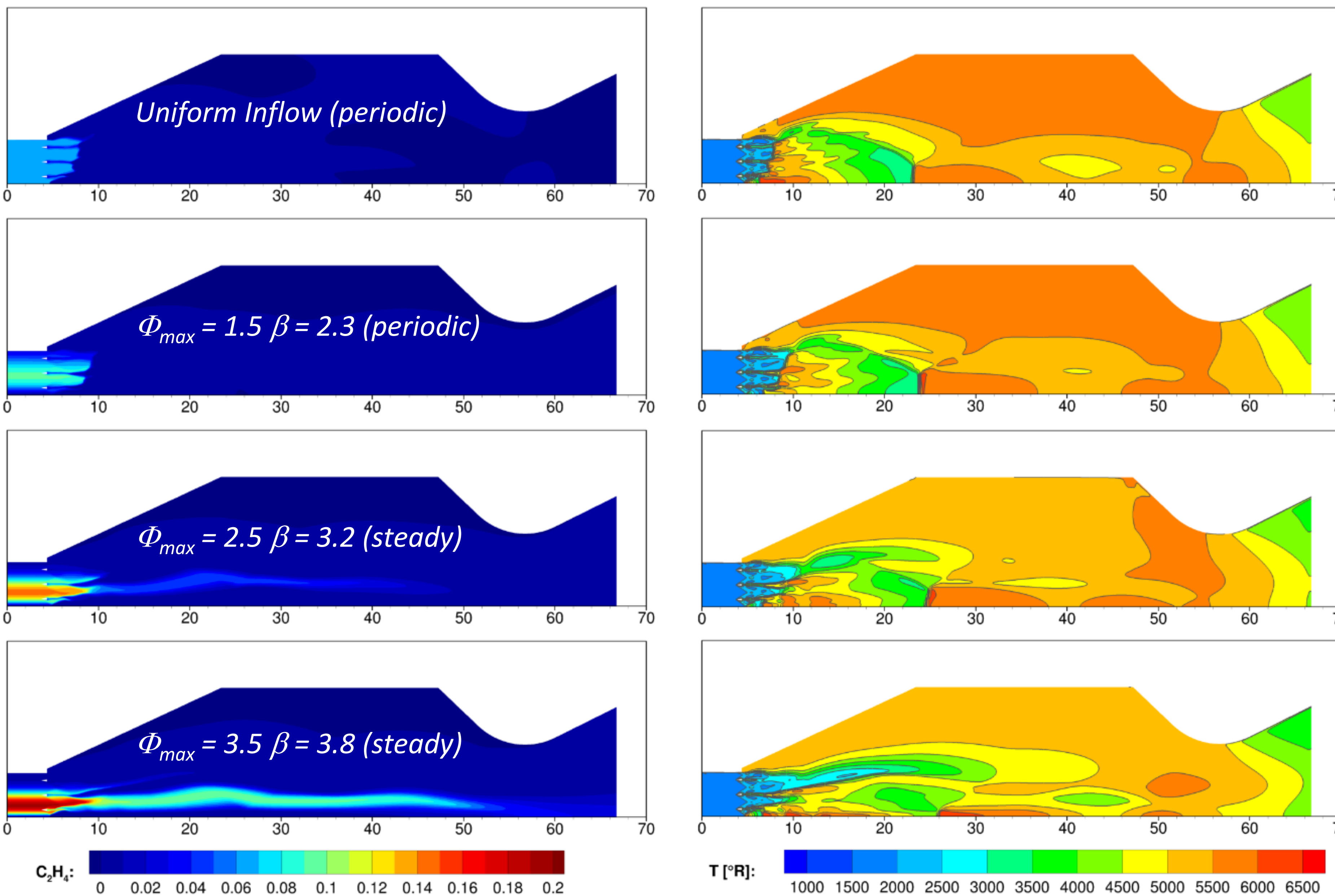



Mach
Number
4.0
0


Ethylene
Mass
Fraction
0.15
0

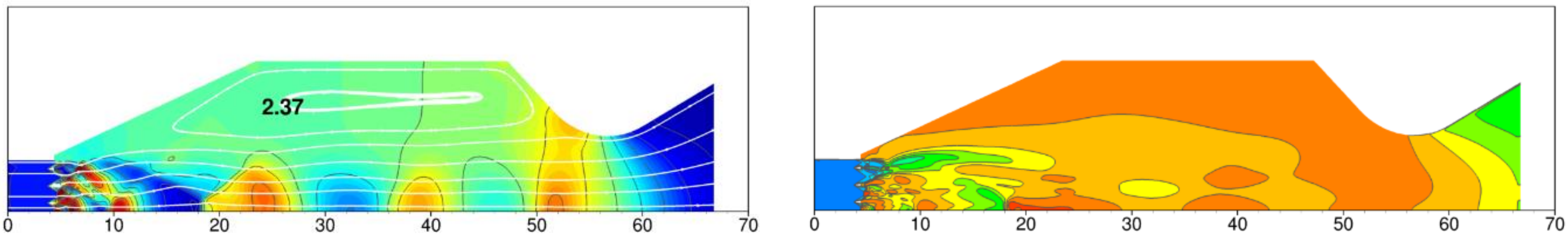
TAFI Finite-Rate Chemistry Results

Effect of Fuel Inflow Profile, Mach 8 Flight Condition

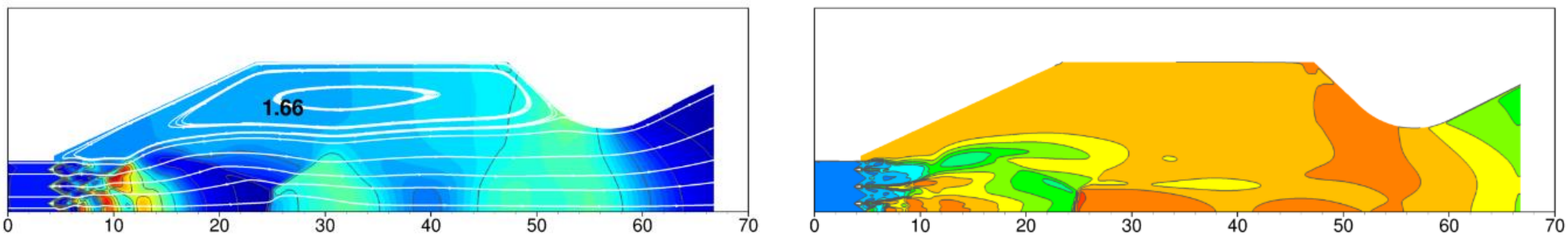


TAFI Finite-Rate Chemistry Results

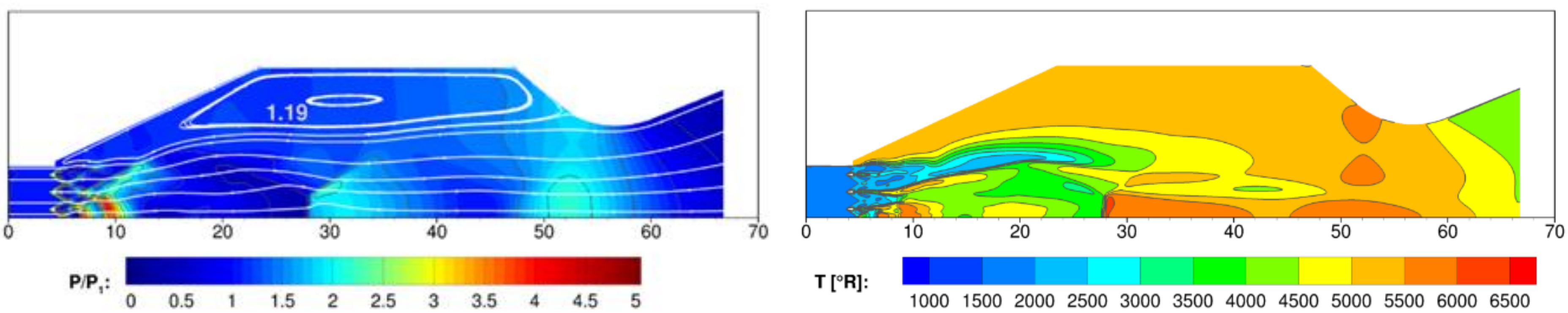
Effect of Nozzle Throat Area, Mach 8 Flight Condition, Φ_{max} = 2.5



A_8 = 80%



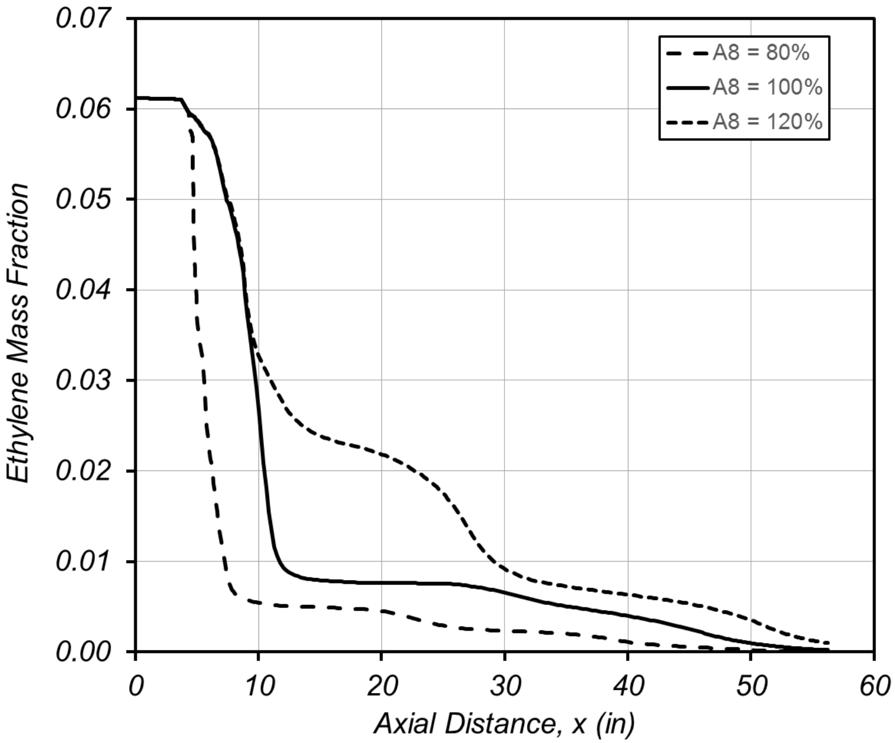
A_8 = 100%

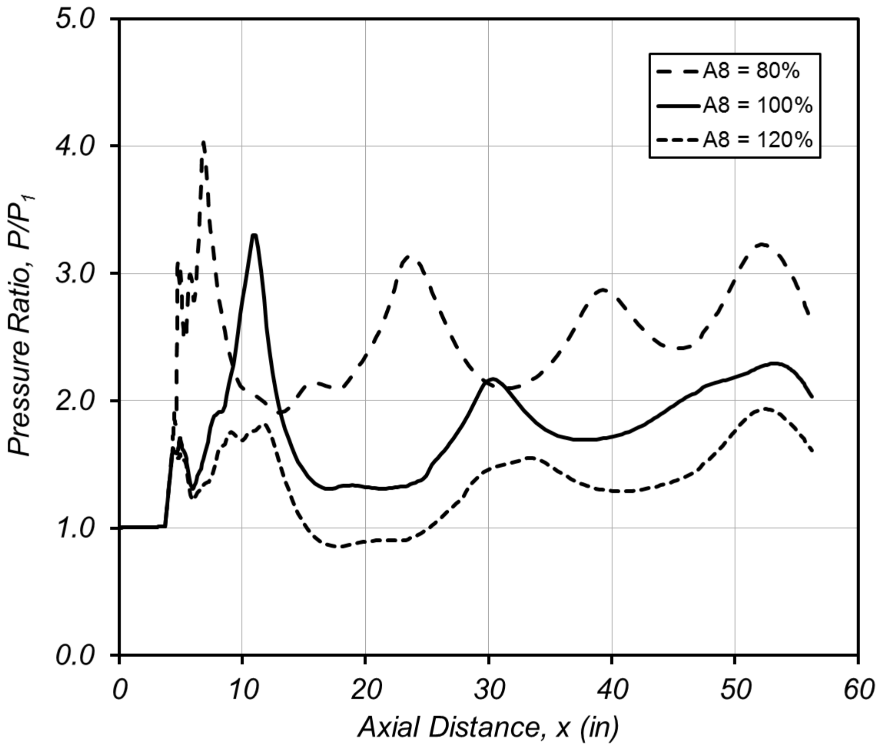


A_8 = 120%

TAFI Finite-Rate Chemistry Results

Effect of Nozzle Throat Area, Mach 8 Flight Condition, Φ_{max} = 2.5

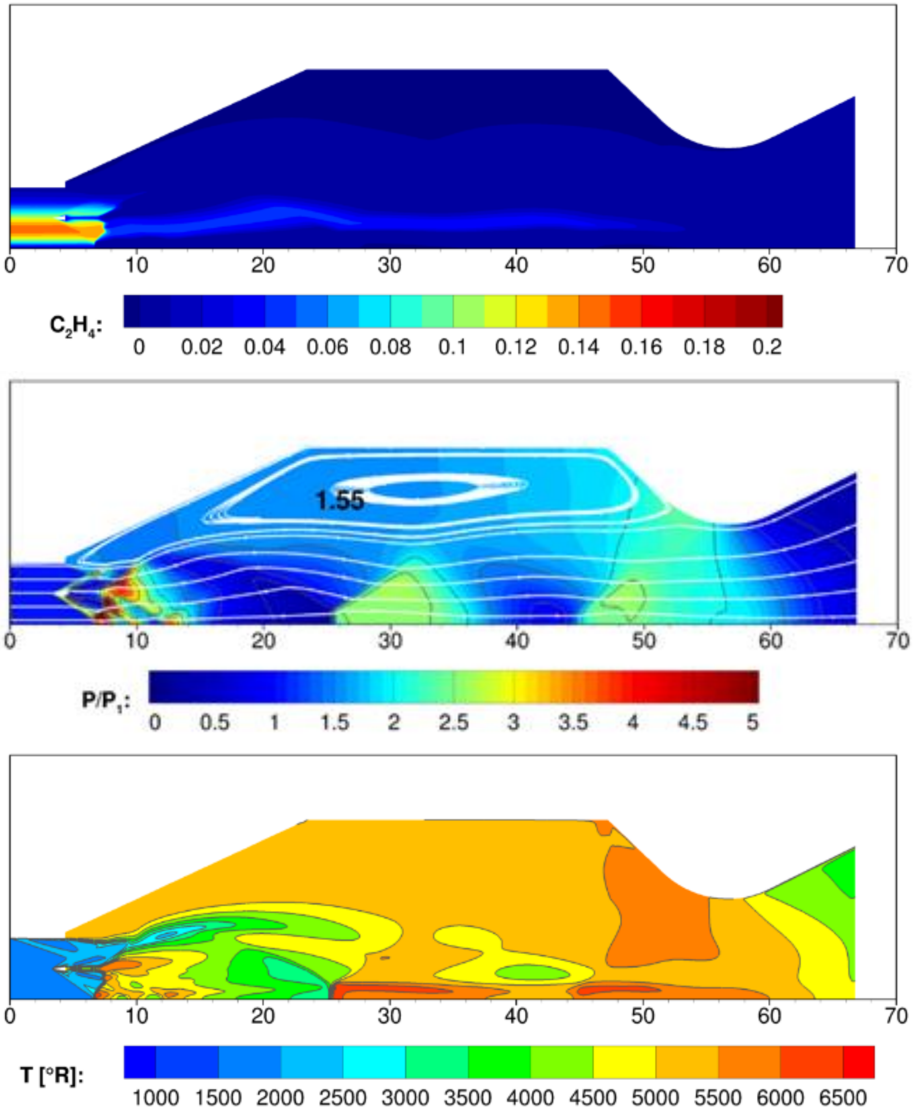




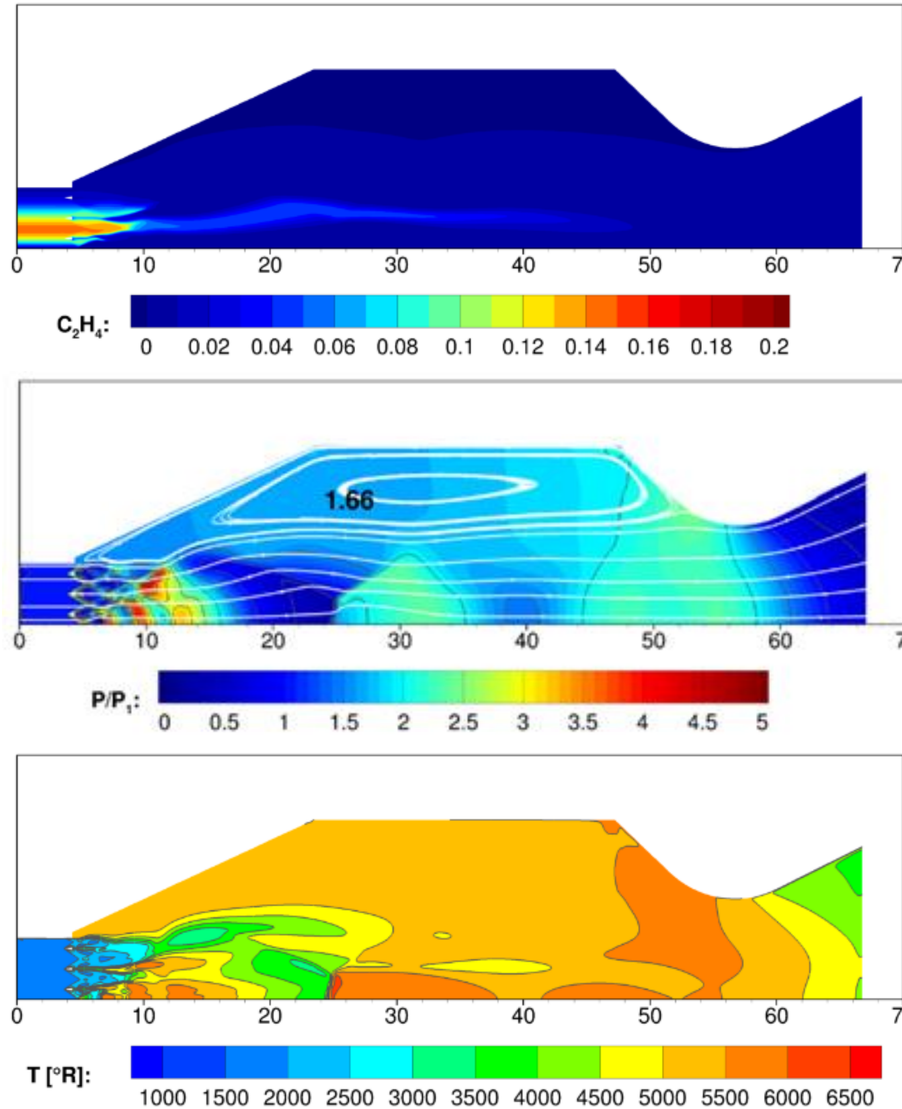
TAFI Finite-Rate Chemistry Results

Single Flameholder, Mach 8 Flight Condition, Φ_{max} = 2.5

Single Flameholder



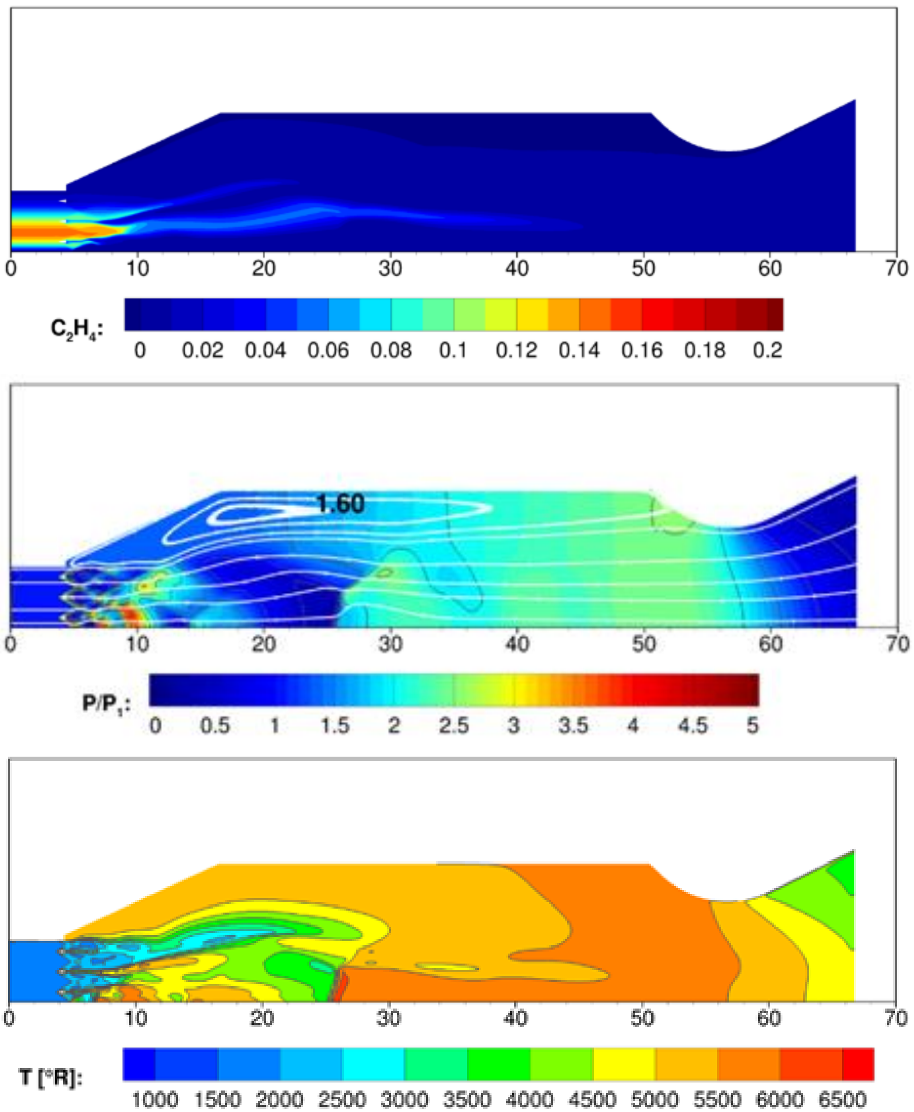
Three Flameholders



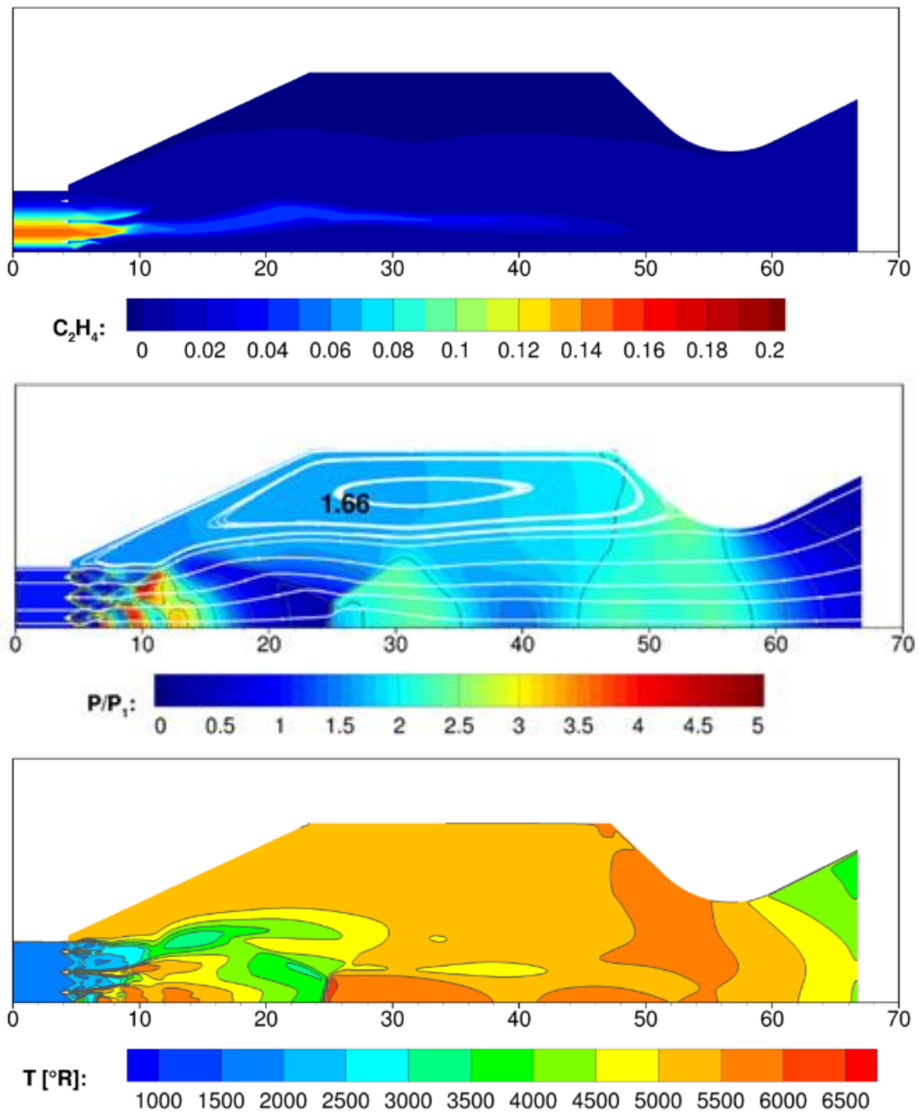
TAFI Finite-Rate Chemistry Results

Reduced Combustion Chamber Diameter, Mach 8 Flight Condition, Φ_{max} = 2.5

60% Combustion Chamber Area

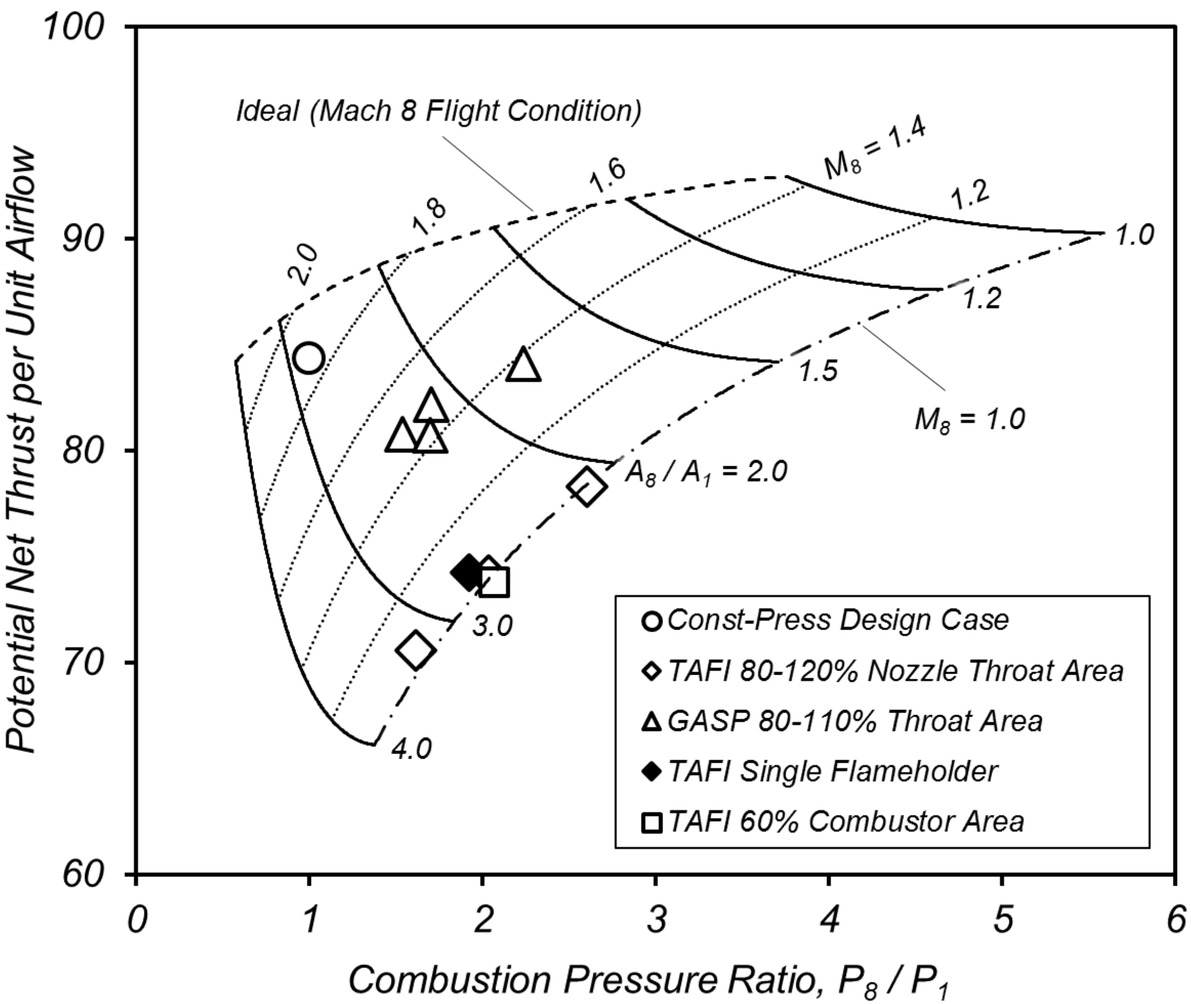


100% Combustion Chamber Area



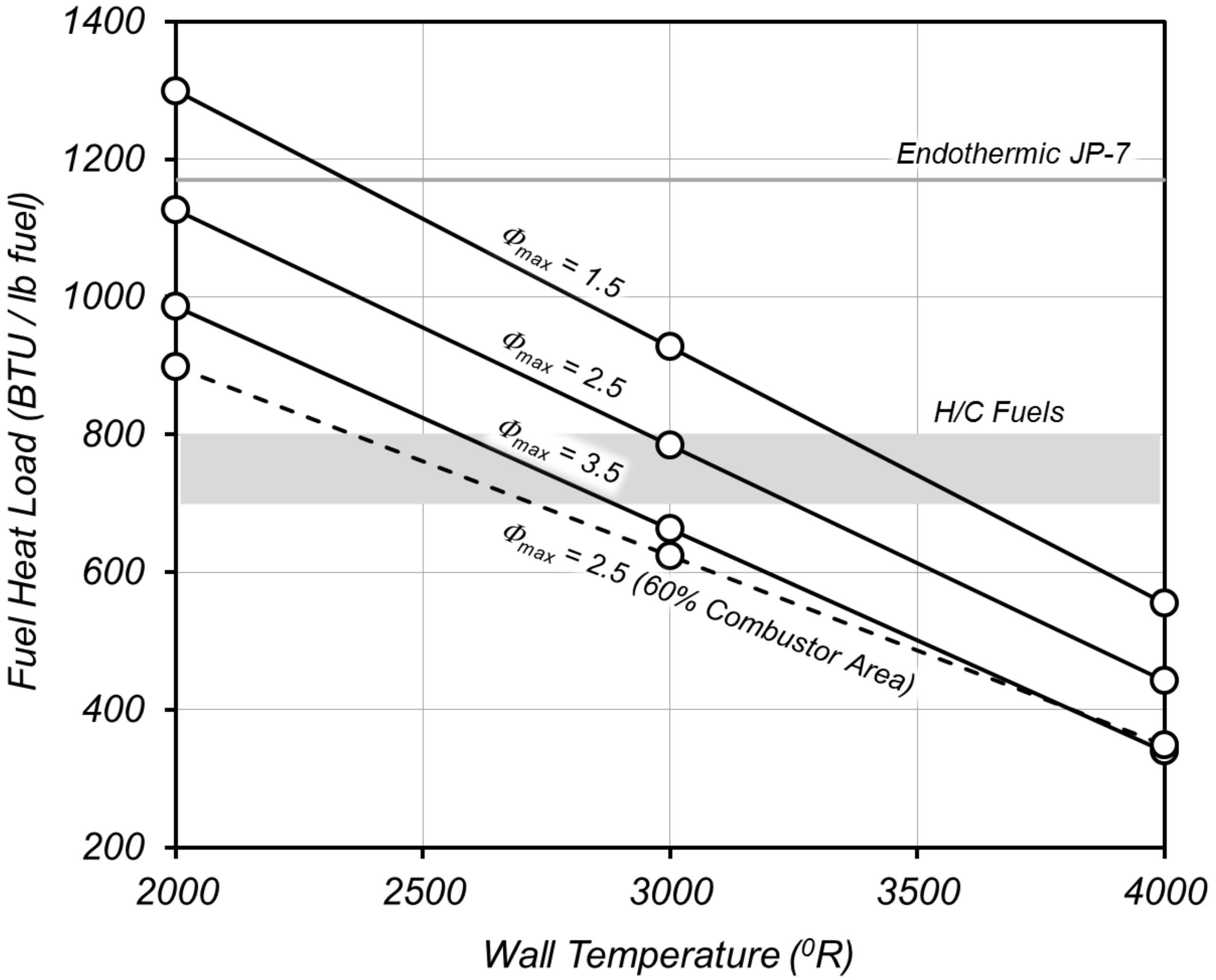
Performance Map for Mach 8 Flight Condition

TAFI and GASP Results Compared to Ideal Scramjet



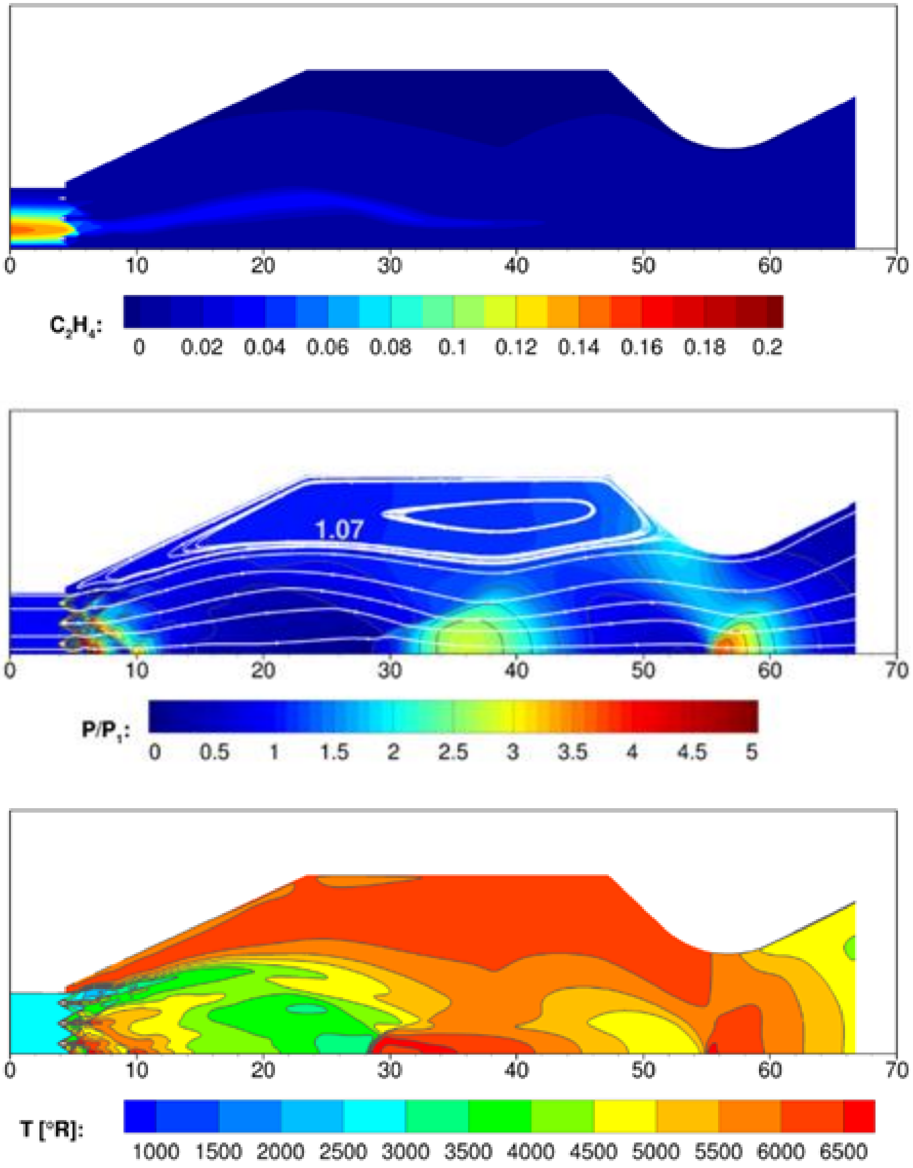
TAFI Finite-Rate Chemistry Results

Effect of Wall Temperature and Φ_{max} on Fuel Heat Load



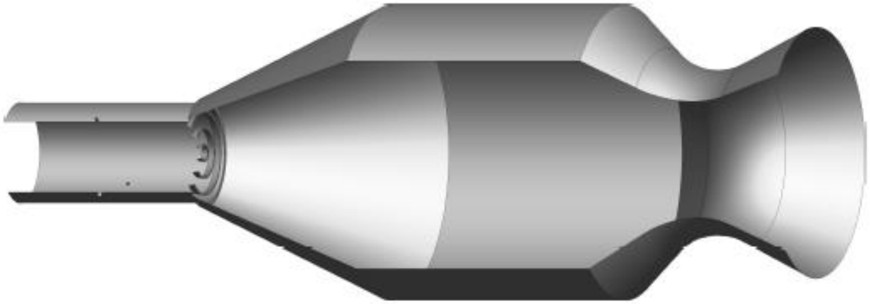
TAFI Finite-Rate Chemistry Results

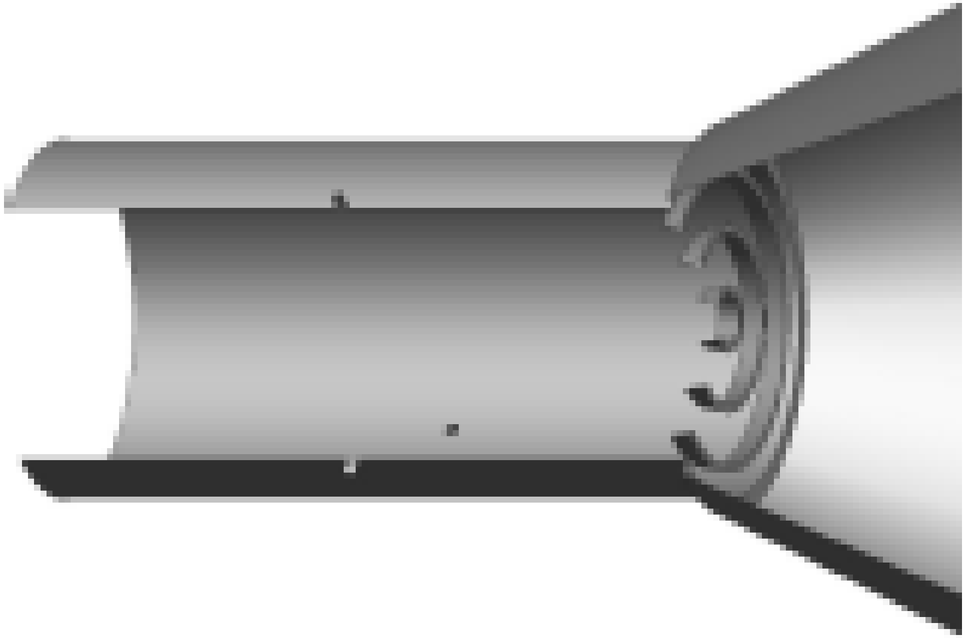
Mach 8 Geometry at Mach 10 Flight Condition, Φ_{max} = 2.5



3-D CFD Using the National Combustion Code

Mach 8 Geometry with Fuel Injection Spool Added





Summary

- A new dual-mode combustor that relies on supersonic combustion in a free jet was introduced
- Free-jet combustion process validated numerically for axisymmetric geometry with a pre-mixed and non pre-mixed fuel-air inflow
- Ignition is enhanced by strong shock waves in the free-jet
- Coupling of ignition delay with free-jet flowfield caused instability
- Net thrust per unit airflow was 70-85 lbs at a flight Mach number of 8 depending on the throat area setting
- Heat load depends on the fuel-air ratio in the free-jet shear layer and is within the capacity of hydrocarbon fuel
- Three-dimensional CFD calculation with discrete fuel injection is underway